

The influence of die geometry and workpiece mechanical properties in T-Shape friction test

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Abstract

In this study, T-Shape friction test was redesigned to make it more suitable for application to microforming processes. Workpiece with aspect ratio (length/diameter) of 5 was proposed in order to ease workpiece handling. The die geometry was also modified from the original test to improve friction sensitivity especially within the range of friction factors commonly observed in metal forming. Geometric deviation of the die was simulated using Deform-2D to establish the acceptable tolerance for the fabrication. The effect of variation in workpiece mechanical properties on the test behavior was also investigated through Deform-2D simulation. Based on simulations on a 1 mm diameter copper workpiece, a tolerance of 0.01 mm (1% of workpiece diameter) was found to be the most suitable for the die fabrication. In addition, it was shown that variations in workpiece mechanical properties of up to 10% do not significantly influence the

friction test results. Ultimately, T-Shape test experiment was conducted using copper workpieces to examine how the test complied with the friction behavior observed in the experiment.

Keywords

T-Shape compression test; friction tests; microforming; friction simulation study

Introduction

Friction in metal forming processes gives rise to redundant energy usage by increasing the process load requirement. Furthermore, friction also influences the tool wear and workpiece flow behavior. Hence, it is important to consider friction in designing metal forming processes. For this purpose, generic friction tests are often used to evaluate the amount of friction occurring during the process. These tests produce friction-dependent behaviors and the results from these tests are then used to define frictional properties in Finite Element (FE) code. The use of generic friction tests allows users to evaluate different materials, lubricants and other tribological conditions within the constraints of metal forming process conditions.

Microforming processes are influenced by size effects as described by Vollertsen et al. (2009) thus creating a deviation in process behaviors as compared to macro metal forming. Most notably, the friction in microforming is influenced by the changes of distribution of closed and open lubricant pockets as presented by Peng et al. (2010), which is not significant in macro metal forming. Lubricant pocket model has been the general agreement in understanding the influence of size to lubrication and it has also been considered by Engel (2006) and Chan et al. (2011).

At the present, the friction studies in microforming are conducted using friction tests developed for macro metal forming processes by scaling down the die and workpiece geometries. Geiger et al. (2001) presented an example on the use of double cup extrusion test in microforming. As they are designed for larger sizes, scaling these tests to microforming size creates difficulties mainly in handling and analysis of the results. This motivates the development of a generic friction test that is reliable and convenient to be conducted at the microforming scale.

This paper reviews notable conventional metal forming friction tests and presents the rationale for selecting a friction test based on the T-Shape test for microforming. The selection criteria include the tests' ease of handling, their characterization and miniaturization, as well as their ability to produce large contact pressure and plastic deformation. Furthermore, this paper describes the modifications made to the original T-Shape test used in the current study. The paper also presents the simulation results using Deform 2D to define an acceptable die geometry tolerance and concludes with the influence of workpiece material properties on the test behaviors, as well as experimental findings.

Reviews of Friction Tests for Metal Forming

Friction tests for metal forming processes were developed to reveal the influence of various process variables, i.e. material selection, tooling surface finish and lubricant used, to the frictional properties during the forming process. Friction tests for metal forming are generally characterized by the high pressure contact produced and high level of plastic deformation. Various friction tests using different test geometries have been introduced, including:

1. Ring Compression Test

Ring Compression Test (RCT, also called ring test) uses a ring workpiece compressed between two flat dies (see Figure 1). The interface friction occurring between the flat dies and the ring workpiece influences the metal flow behavior during the test. Consequently, the geometry of finished workpiece can be examined to investigate the magnitude of friction during the test by matching experimental results with known calibration curves. Male and Cockroft (1964) produced an example of calibration curves for RCT based on Coulomb friction coefficients using workpiece geometry ratios of external diameter to internal diameter to height of 6 to 3 to 2 (6:3:2). Several studies reviewed by Danckert and Wanheim (1988) suggested that the workpiece geometry ratio of 6:3:2 has been accepted as the unofficial standard for RCT. The use of RCT to investigate microforming size effects has been presented by Messner et al. (1994) with ring external diameter as small as 1 mm.

Danckert and Wanheim (1988) published a benchmark work revealing that when constant friction factors are used to produce the calibration curves for RCT, the calibration curves are influenced greatly by the calibration approach (e.g. theoretical consideration or simulation algorithm) and by the strain hardening behavior of the material especially when friction is high. In order to investigate the influence of the contact pressure distributions to friction, Tan et al. (1998b) produced a set of alternative ring geometries for RCT and discovered that the strain hardening of the material influences the distribution of contact pressure, which subsequently influences friction.

2. Spike Forging

Spike Forging (SF, see Figure 1) geometry was introduced in a FE analysis by Oh (1982) and was used to simulate non-isothermal forging and heat transfer by Im et al. (1988). The SF geometry was proposed as a suitable friction test for forging application by Isogawa et al. (1992) and was claimed to be more suitable for forging applications than RCT as it produces higher contact pressure and higher new surface generation. Using SF, friction can be characterized by examining the spike height, the forging load, or the ejecting load to remove the finished workpiece.

Xu and Rao (1997) further explored the influence of the die and workpiece geometry to the SF test behavior and defined an optimum workpiece aspect ratio (length/diameter) of 0.5 in order to have both upsetting and extrusion deformation and the most severe metal flow. This aspect ratio also provided highest spike height sensitivity to friction.

3. Backward-Can Forward-Rod Extrusion

Backward-Can-Forward-Rod Extrusion (BCFRE, see Figure 1) was introduced by Kuzman et al. (1996) to replicate the metal flow behavior in the real bulk metal forming process. Another use of BCFRE was presented by Geiger et al. (2001) in microforming scale to investigate how metal flow changes when the grain size of the material is comparable to the width of the extrusion channel.

4. Double Cup Extrusion

Double Cup Extrusion (DCE, also called double forward-backward extrusion, see Figure 1) was introduced by Buschhausen et al. (1992) and is a very popular friction test for bulk metal forming. Its use for microforming friction investigation was presented by Geiger et al. (2001)

which ultimately showed the trend of increasing friction with miniaturization. In studies on larger scale, Tan et al. (1998a) and Schrader et al. (2007) showed that DCE test behavior is also influenced by the initial state of the material (annealed or work hardened), strain hardening exponent and the detail geometry of the tooling. Hence, it is important to present the calibration curves used in the analysis together with the experimental results while presenting the conclusion of DCE.

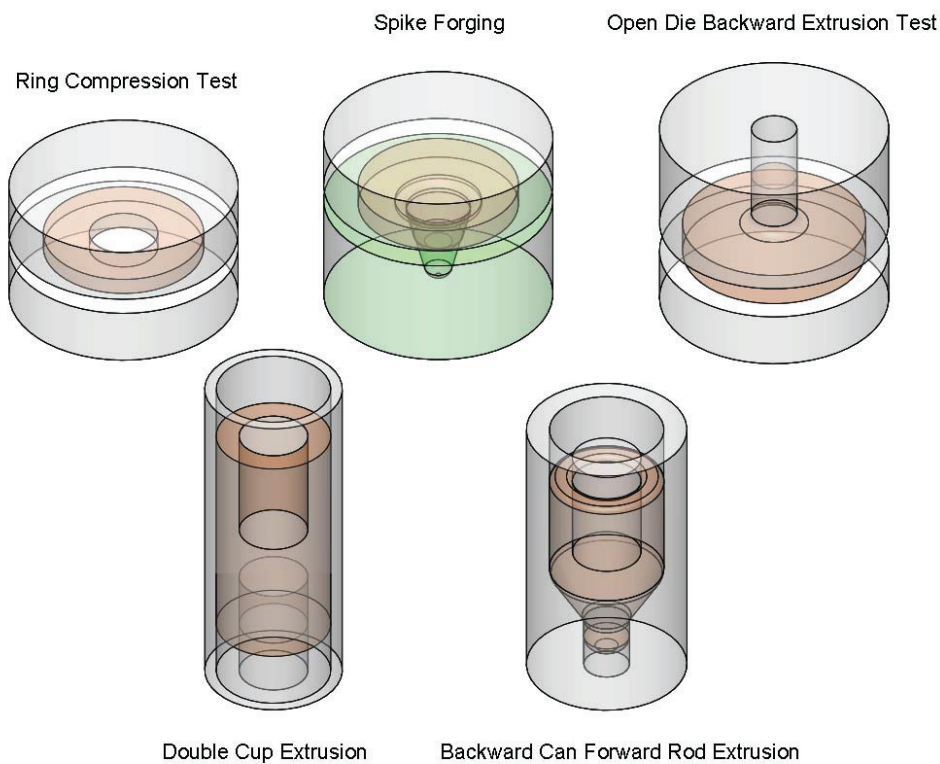


Figure 1: Illustration of Friction Tests (1)

5. Open Die Backward Extrusion Test

Sofuoglu and Gedikli (2002) proposed the Open Die Backward Extrusion Test (ODBET, see Figure 1) as an alternative to RCT to use as a friction test for metal forming. ODBET was

designed primarily to allow high level of plastic deformation to the test workpiece. Similar geometry was used by Ghassemali et al. (2011) to investigate metal flow and friction in micro pin forming. In OBDET, the amount of friction occurring at the material interfaces would influence the amount of backward extrusion flow.

6. Cylinder Compression

Ebrahimi and Najafizadeh (2004) proposed that the barreling or bulging behavior during Cylinder Compression (CC, also called barreling test as shown in Figure 2) can be used to indicate the amount of friction occurring at the material interfaces. In other word, the amount of barreling is dependent on the magnitude of friction occurring at the interfaces, i.e. more severe barreling corresponds to a higher friction. In performing CC as friction test, users are required to record the diameter of the workpiece both at the ends of the cylinder (at the interface with the tooling) and at the half-length of the cylinder during material deformation.

7. Forward Extrusion

Forward Extrusion (FX, see Figure 2) was introduced by Krishnan et al. (2007). Unlike the friction tests which have been reviewed earlier, FX uses fixed metal flow to characterize friction. In other word, the same amount of stroke in FX produces the same finished workpiece geometry regardless of the friction. Therefore, since the extrusion load in FX is used to deform the material and overcome friction simultaneously, the difference between two FX extrusion loads can be related to the magnitudes of friction in these tests when the material is unchanged.

8. T-Shape Test

T-Shape test (see Figure 2) proposed by Zhang et al. (2009) produces large plastic deformation and high contact pressure similar to that in cold forging processes. Friction in the T-Shape test gives rise to competition of metal flow in the extrusion direction and the upsetting direction which further affects the test behavior in terms of both metal flow and process load.

9. Tip Test

Backward extrusion test or known later as Tip Test (TT, Figure 2) by Im et al. (2002) combines the processes of upsetting and backward extrusion. The geometry used in TT is similar to the bucket test introduced by Shen et al. (1992). During the test, the process load is recorded throughout the stroke as a measure of friction between the workpiece and the extrusion channel.

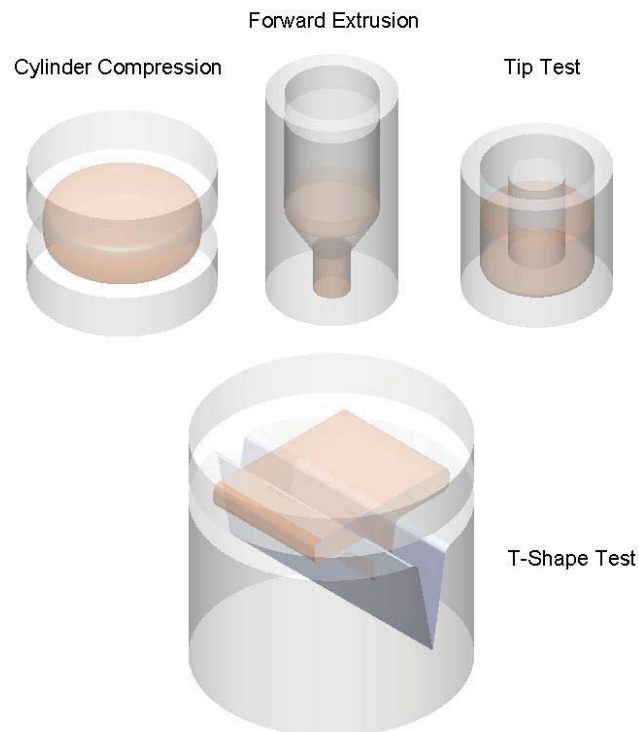


Figure 2: Illustration of Friction Tests (2)

Requirements of Friction Test for Microforming

Various friction tests for metal forming have been proposed with different test geometries and different methods of characterizations. Users need to match the experimental results from these friction tests against known calibration curves. These calibration curves can be produced from either theoretical derivation (e.g. Danckert and Wanheim (1988)) or simulation methods (e.g. Tan et al. (1998b) and Schrader et al. (2007)). These calibration curves are not universal. As a result, new calibration curves need to be produced when a new material is used.

The decision on a suitable friction test for microforming should consider the friction sensitivity of the test and additional factors as indicated below:

1. Scalability of the setup

Geiger et al. (2001) suggested the characteristics of microforming to encompass forming processes that produce components with at least two dimensions measuring less than 1 (one) millimeter. Hence, the friction test for microforming should be able to be scaled down to micro sizes without severe complications.

Qin et al. (2008) suggested that the tooling design in sheet microforming is constrained by the capability to fabricate the tooling, i.e. forming dies, and the cost of fabrication. Therefore, friction test for microforming should not depend on internal surfaces as these surfaces cannot be fabricated and characterized accurately. Moreover, the test should not rely on very intricate

tooling geometries which require tight tolerances. Ultimately, the test should use a geometrically simple workpiece to avoid complication during workpiece fabrication and minimize cost.

For example, fabrication of internal diameter in RCT workpiece would be significantly more difficult at small size and therefore needs to be avoided. Other scaling difficulties include the production of internal contact surfaces for extrusion channel such as in DCE, FX and so on. In considering a friction test, it is desirable to have excellent control and characterization of the surface finish of the contacting surfaces. Fabrication and characterization of internal surface finish are difficulties which need to be avoided.

2. Characterization approach

When friction size effect needs to be examined, friction test design should ensure that the readings and measurements extracted from the test are not affected by material size effect.

Dieter et al. (2003) showed that the material flow stress is influenced by the ratio of the workpiece size to its grain size. Surface layer model by Engel et al. (2007) explains that the load requirement is not directly proportional to the size of the setup. In essence, the model considers two different mechanical properties in one part, bulk grains mechanical properties and free surface grains mechanical properties. As a result, although the process load is influenced by friction, a change in process load in the microforming test does not always correspond to a change in friction. Hence, the friction characterization should not depend on the process load. In this regard, friction tests which rely solely on the measurement of the process load such as FX are not ideal for microforming application. Finally, measurements of complicated finished geometries should be avoided.

3. Handling

The test should be designed for easy set up and manipulation despite the small test workpieces. For example in SF, placing the workpiece to be perfectly concentric or axisymmetric in the fixture is not a problem when the workpiece size is large. However, when the workpiece is scaled to a small size, additional accessories or features need to be introduced to aid in handling.

4. Contact pressure at the tool-workpiece interface

In order to simulate the contact conditions during bulk metal forming, the friction test should be able to reproduce high contact pressures. Petersen et al. (1997) suggested that the magnitude of the contact pressure determines the contact behavior ultimately resulting in the change of friction based on slip line fields analysis. Contact pressure evolution is generally influenced by the amount of strain and strain hardening occurring during the friction test as well as the amount of free surfaces. For example, RCT produces relatively smaller strain during testing and the open die configuration allows more free surfaces; consequently, it produces lower contact pressure in comparison to T-Shape (see Zhang et al. (2009)).

5. Level of material plastic deformation

When FE code is used for friction investigation, the constant shear friction model $\tau = mk$ or the general friction model by Petersen et al. (1997) is usually used to represent the friction behavior. These friction models track shear stress progression during deformation and use the shear stress data to calculate friction. As bulk metal forming processes generally produce large

plastic deformation, a friction test with large plastic deformation can therefore simulate the real process conditions more accurately.

Table 1 summarizes several known friction tests for bulk metal forming and their suitability to be implemented as the bulk microforming friction test.

Table 1: Summary of available friction tests

Test Name	Reference	1	2	3	4	5
Ring Compression (RCT)	Male and Cockroft (1964)	X	O	O	X	X
Spike Forging (SF)	Isogawa et al. (1992)	X	O	X	O	O
Backward-can Forward rod Extrusion (BCFRE)	Kuzman et al. (1996)	X	O	O	O	O
Double Cup Extrusion (DCE)	Geiger et al. (2001)	X	O	O	O	O
Open-die Backward Extrusion (ODBET)	Sofuoglu and Gedikli (2002)	X	O	X	O	O
Tip Test (TT)	Im et al. (2002)	X	X	X	O	O
Cylinder Compression (CC)	Ebrahimi and Najafizadeh (2004)	O	X	O	X	X
Forward Extrusion (FX)	Krishnan et al. (2007)	X	X	O	O	O
T-Shape Test	Zhang et al. (2009)	O	X	O	O	O

Criteria: 1 Scalability of the setup

 2 Characterization approach

 3 Handling

 4 Contact pressure at the tool-workpiece interface

 5 Level of material plastic deformation

Remarks: O – Suitable , X – Not Suitable

Evaluation of different T-Shape Test designs

Plane strain test with existing geometry

The original T-Shape test introduced by Zhang et al. (2009) (Figure 3) is proposed as a suitable friction test for microforming application based on the selected criteria (see Table 1).

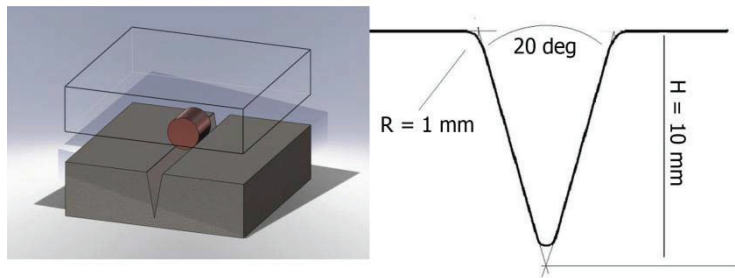


Figure 3: (Left) Illustration of T-Shape test setup (Right) Die geometry of T-Shape test

In T-Shape test, friction influences load and metal flow behavior. Each friction factor produces a unique graph of metal flow against load. By fitting experimental data to calibration curves obtained from the simulation (using the mechanical properties of the tested workpiece and various friction factors), users can establish the magnitude of friction involved in the T-Shape test. In order to filter the influence of mechanical properties size effects during miniaturization, stroke (displacement of moving die during the test) is proposed to replace load as independent variable. Consequently, both the load and the evolution of the workpiece geometry would be recorded as a function of the stroke, as described by Taureza et al. (2010). Furthermore, the original 1:1 cylinder aspect ratio is replaced with a workpiece with the length to diameter ratio (l/d) of 5 or higher. Although the workpiece with higher aspect ratio requires higher load to deform, this modification eases handling. When applicable, the aspect ratio of the workpiece can

be increased even further to reduce simulation time. High aspect ratio would restrict axial material flow especially at the mid-length of the specimen. Therefore, 2D plane strain simulation can be used instead of 3D simulation. The current simulations to investigate of the influence of die geometry and workpiece mechanical properties to the process behavior were performed in 2D plane strain geometry to reduce computational cost and allow observation on various parameters.

Normally, the stroke applied to the workpiece is always smaller than the stroke prescribed to the press machine because of the equipment elastic deflection. However, in the modified T-Shape, friction is evaluated by measuring the *total height* and the *flange height* at the mid-length of the workpiece as illustrated in Figure 4. This way, users are allowed evaluate the results of the T-Shape test without considering possible equipment elastic deflection.

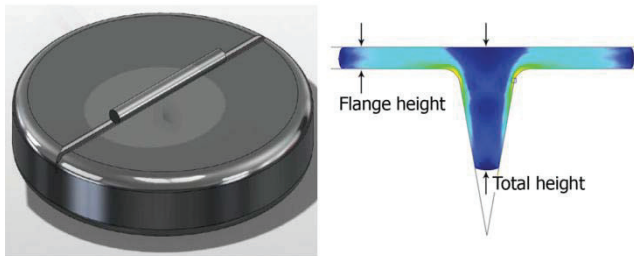


Figure 4: (Left) T-Shape with plane strain specimen (Right) Evaluation of T-Shape geometry

For the simulation, the material data used was obtained from the upsetting of ETP Copper. The diameter of the upsetting workpiece was $D = 1$ mm and $L = 1.5$ mm. The analysis using Deform 2D was done using an updated Lagrangian mesh. The small upset workpiece dimension was selected to capture the behavior of the material at sub-millimeter scale.

The stress-strain curve of the ETP Copper is provided in Figure 5 (solid line). This set of data was then used as an input for the Deform 2D simulation, using rigid bodies for the dies, and rigid plastic material model with approximately 2000 elements for the workpiece. The sensitivity of the original T-Shape test die was evaluated using Deform 2D with plane strain assumption. The FE results are shown in Figure 6. Moreover, two additional stress strain curves (90% and 110% flow stress) were generated to be used in the simulation to examine the influence of inconsistencies in material properties to the process behavior.

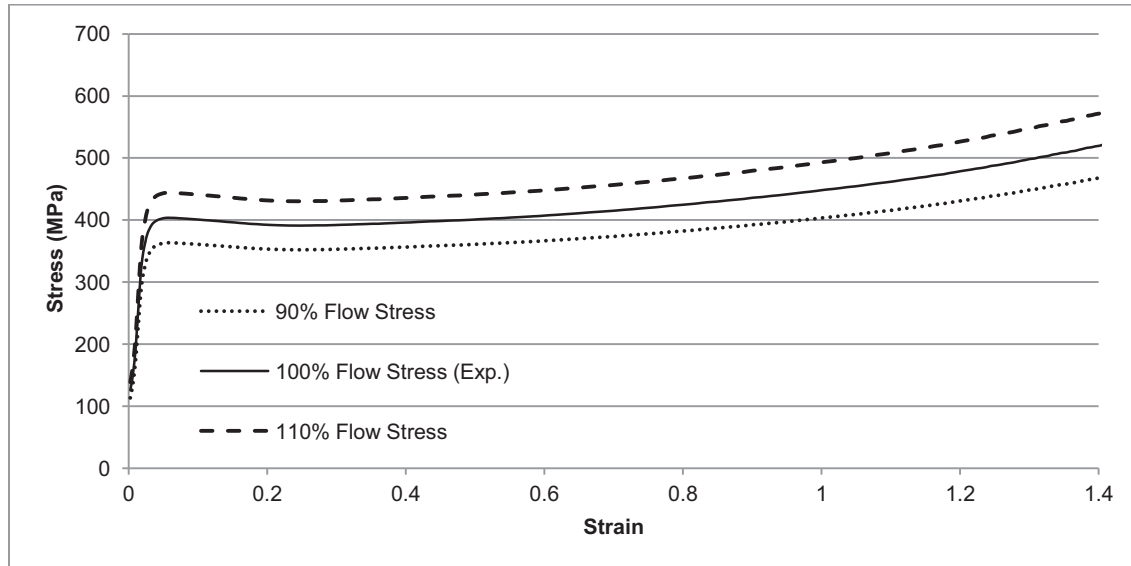


Figure 5: Stress v Strain of upset workpiece

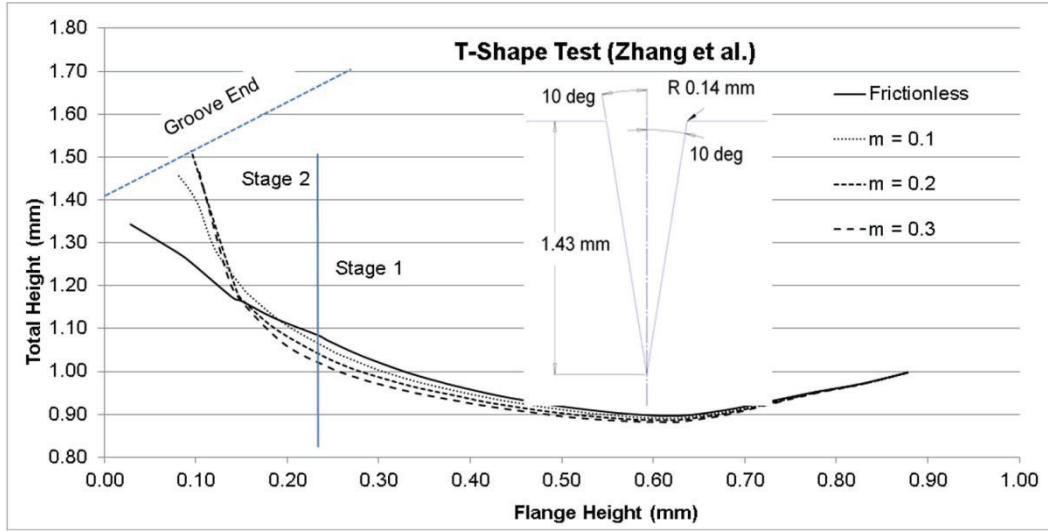


Figure 6: Evaluation of original T-Shape die. Inset: Die geometry

The die was scaled down in this simulation to maintain a workpiece diameter of 1 mm. The original T-Shape test was designed to work with workpiece of 7 mm in diameter. Hence, in the simulation, the die prescribed by Zhang et al. (2009) was scaled by a factor of 1/7. There are two directions in which the material can flow during the T-Shape test; it can flow into the groove (extrusion flow) or outwards (upsetting flow).

All simulations in the present study use constant shear friction model and various constant friction factors m are used to produce the calibration curves. During the initial phase of T-Shape test, called Stage 1, the area sensitive to friction is the groove area (for extrusion flow). The narrow groove produces friction inhibiting material flow into the groove. Hence, during Stage 1, higher friction generally results in less extrusion flow and subsequently a lower total height. As the material continues to flow outwards, there is a material build-up between the parallel surfaces of the die and the punch. This creates high friction restricting subsequent upsetting flow and at this point the test moves into Stage 2. During this stage, high friction produces less upsetting

flow and consequently, more extrusion flow (same stroke produces higher increase in total height).

Observing Figure 6, a clear separation of behaviors obtained from the different friction factors can only be seen from flange height 0.05 mm to 0.15 mm for the 1 mm workpiece. Also, using the proposed characterization approach, the original T-Shape test geometry is only able to distinguish a narrow friction range below $m = 0.2$. It is also noted that metal flow in the original T-Shape geometry is limited by the groove depth as marked with the dotted line in Figure 6 (Groove End).

Two-slope T-Shape (T-Shape A)

Upon examining the FE simulation results (Figure 6), it was understood that the clear distinction of material flow produced from the different friction factors could only be realized at Stage 2, and that Stage 1 and Stage 2 are counteracting each other in producing the protrusion. Therefore, the objective of the die modification is to suppress Stage 1 to allow distinction of material flow to develop in Stage 2. In other word, the die modification should shift the transition between Stage 1 and Stage 2 to an earlier time (to larger flange height).

T-Shape A with two-slope design is then proposed and its evaluation is presented in Figure 7. Simulation with the two-slope design shows that the geometry can suppress Stage 1 and amplify Stage 2. The very narrow groove at the bottom of the die is designed considering workpiece characterization. In T-Shape test, the friction between workpiece and tooling affects the amount of extrusion flow and upsetting flow. With narrower groove at the bottom of the die, the test can

resolve a smaller change in friction and extrusion flow. In other word, the change in extruded volume is translated into a larger change in extruded length or total height.

The wider groove at the opening effectively suppresses Stage 1 by generating material build-up between the flat dies more immediately. However, the limitation of T-Shape A lies on the maximum extruded length which entirely depends on the depth of the groove. Even though the extruded length or total height is more friction-sensitive, this friction sensitivity cannot be utilized fully as the extruded length is limited by the groove depth as shown by the dotted line in Figure 7 (Groove End).

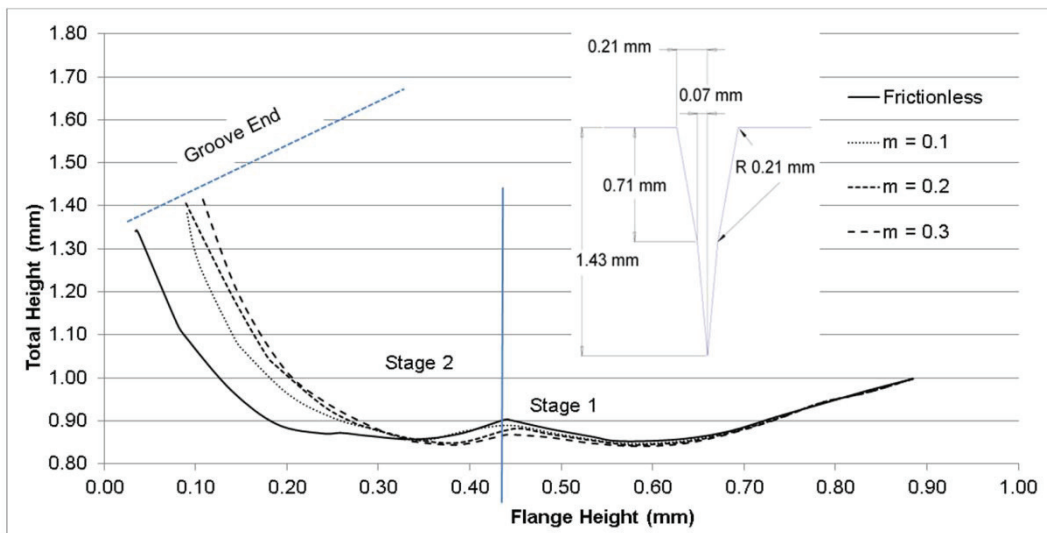


Figure 7: Evaluation of T-Shape A. Inset: Die geometry

Groove with Vertical Wall (T-Shape B)

By changing to a vertical wall, the distinction between different friction curves was further increased and there was no limitation to extrusion flow and total height, as illustrated in Figure 8.

Since the top portion of the groove remains similar to that of T-Shape A, the behavior of the material flow remains similar in Stage 1.

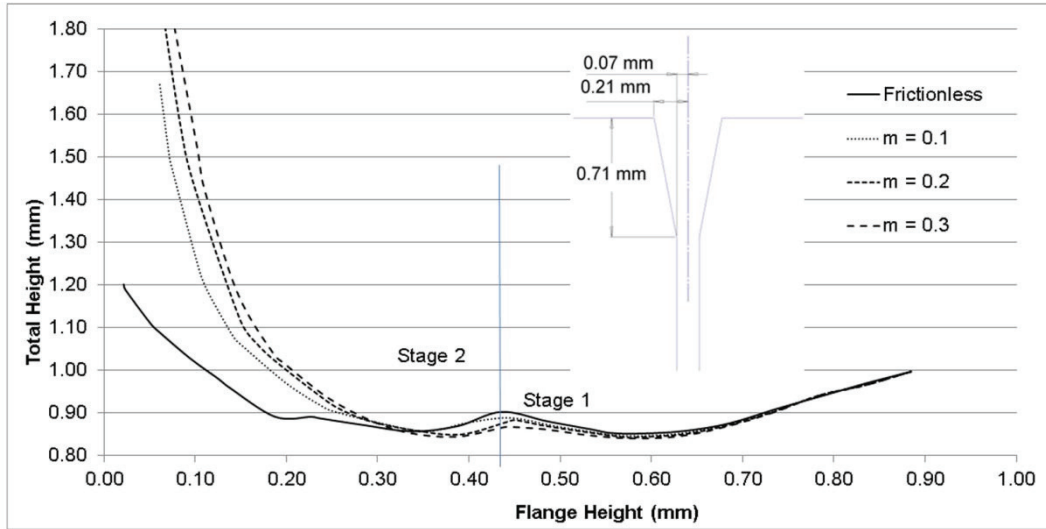


Figure 8: Evaluation of T-Shape B die. Inset: Die geometry

The process load was also evaluated and compared between T-Shape B and the original T-Shape die, as shown in Figure 9. The process load is increased by 18% for frictionless condition, and the increase is even higher when friction exists. The larger difference in process loads from different friction factors is a good characteristic for distinguishing friction conditions. Hence, the T-Shape B design is proposed as the suitable die geometry for microforming friction test.

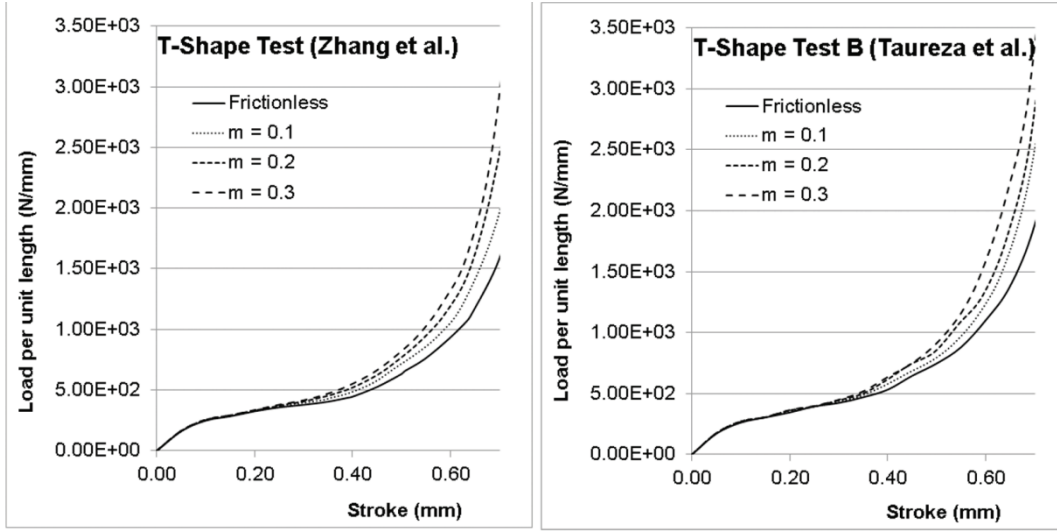


Figure 9: Process load comparison: (Left) Original T-Shape die (Right) T-Shape B

In the experiment, measurements (see Figure 4 Right) can be done at several stroke positions (different flange heights) and the corresponding total heights can be measured directly. The data pairs (flange height and total height) obtained from the experiment are then treated as discrete data points for comparison with the simulation results.

Evaluation of Performance

Figure 10 shows the calibration curves for the original T-Shape design with a workpiece size of 1 mm. Region with the highest resolving capability (flange height 0.11 mm, marked with vertical line) was selected as an ideal point of measurement. However at this point, the geometry was not able to distinguish friction when the magnitude of friction exceeded $m = 0.2$. It was also noted that total height was limited by the groove depth.

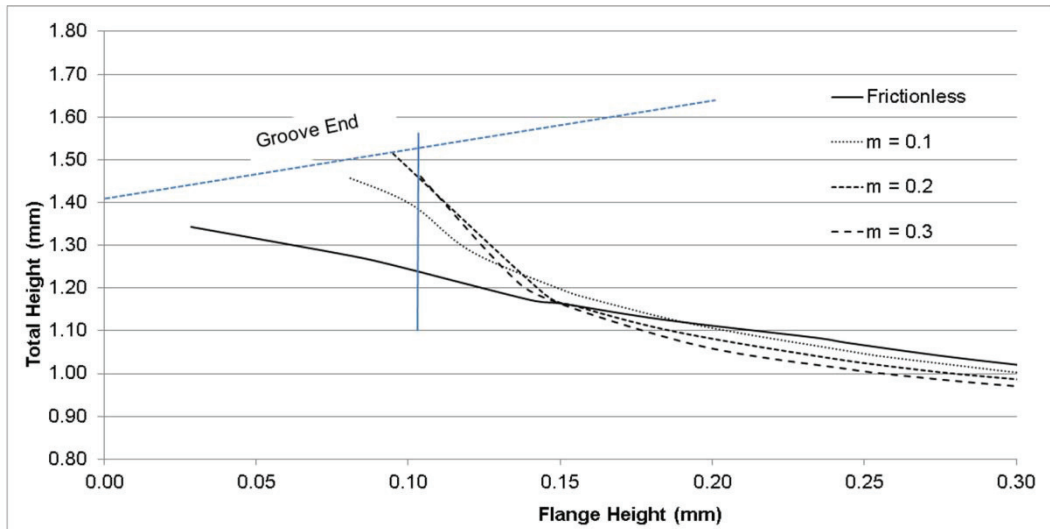


Figure 10: Friction curves for the original T-Shape test

Similar plot is drawn for the T-Shape B (Figure 11). In T-Shape B, the region with the highest resolving capability is at a flange height less than 0.2 mm (marked with vertical line at 0.08 mm as an example).

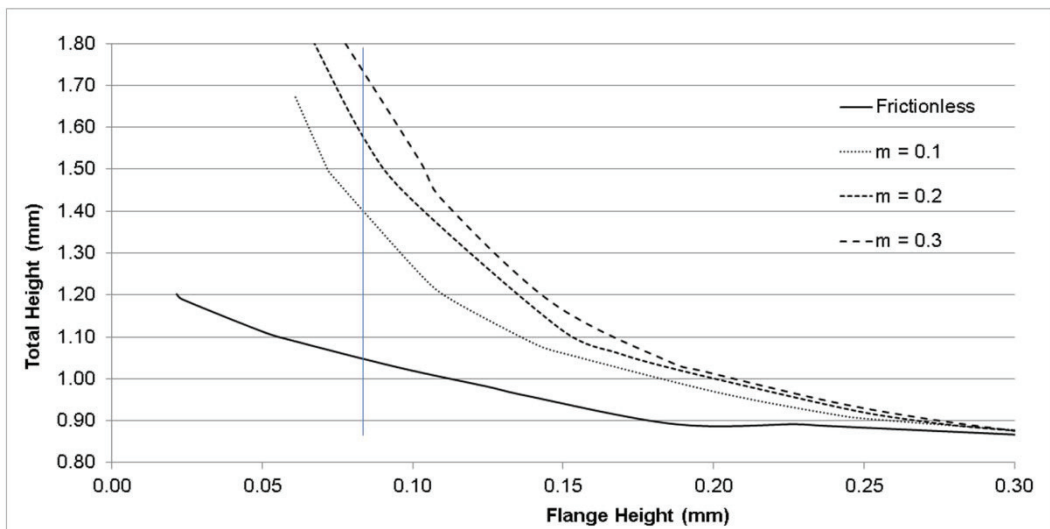


Figure 11: Friction curves for T-Shape B

The improvement obtained by T-Shape B is summarized in Table 2. Table 2 compares the separation of the friction curves with the varying friction factors. When two curves are more widely separated, it will be easier to distinguish different friction conditions in the experiments, thus the test could be considered to be more friction sensitive. For example, at the same flange height in case of the comparison between frictionless and $m = 0.1$, the test which can give a difference (δ) of 0.35 mm in total height between two friction conditions is considered to be better than the test which can only give δ of 0.11 mm.

Table 2: Comparison between original T-Shape design and redesigned T-Shape B

Friction Levels in Comparison	Separation in Original T-Shape test ¹ (δ_0) in mm	Separation in T-Shape B ² (δ) in mm	Performance Index PI = $\delta/\delta_0 \times 100\%$
Frictionless – $m = 0.1$	0.11	0.35	>300%
$m = 0.1 - m = 0.2$	0.08	0.17	>200%
$m = 0.2 - m = 0.3$	0	0.15	-
	¹ Measured at flange height 0.11 mm	² Measured at flange height 0.08 mm	

Figure 12 shows the components of the T-Shape B testing equipment. The assembly consisting of four components is proposed. The T-Shape die is designed as split dies. This design eases fabrication and control of surface finish and surface engineering (e.g. texturing, heat treatment, coating), eases the removal of the finished workpiece without creating additional strain on the workpiece, and also enables users to investigate the condition of the dies after experiment, e.g. look for galling and wear marks. The plane strain workpiece is placed lying down on the groove formed by the split dies. The split dies are housed in a container and are

compression fitted using screws to compensate the pressure exerted during loading and ultimately avoids elastic deflection.



Figure 12: Illustration of T-Shape assembly

Effects of Deviation in Material Properties and Die Geometry

Deviation in Material Properties

In order to fully evaluate the suitability of the T-Shape B for microforming friction tests, series of more thorough simulations were carried out to examine the effects of possible scatters in material properties as well as die inaccuracy. The objective of this investigation is to determine whether the influence of the scatter in material properties to the experimental results shows any significance in comparison with the change of experimental results due to changing friction conditions. The mechanical properties of 90% and 110% flow stress from Figure 5 were considered as possible scatter of mechanical properties.

Figure 13 shows the simulation results after changing mechanical properties of the material in T-Shape test. For each of the three mechanical properties, two friction conditions were simulated: high ($m = 0.3$) and low (frictionless).

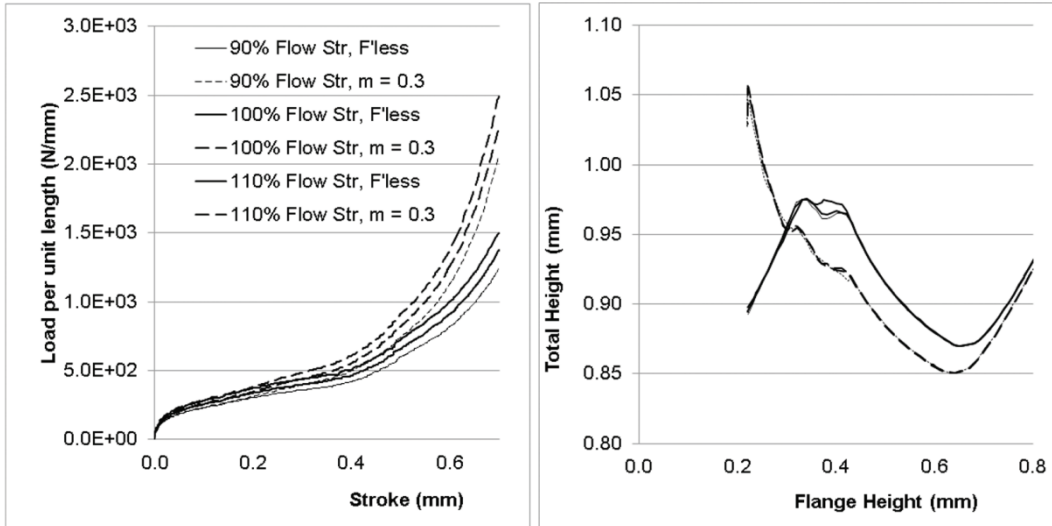


Figure 13: Effect of material properties to T-Shape test

In conclusion, although scatter of mechanical properties of the materials may influence the load, the metal flow behavior during T-Shape test is not influenced by the $\pm 10\%$ variation in mechanical properties. This is a desirable characteristic, i.e. users should be able to examine the results from the test and determine whether the change in test results is due to the influence of friction or due to the mechanical properties. However, the observation by Danckert and Wanheim (1988) on requirement to recalibrate the friction curves needs to be considered when the mechanical properties of the workpiece are significantly different. The change in value of strain hardening exponents in metal forming applications alters the strain distributions in the workpiece, and subsequently alters the distribution of contact pressures at the interface. As such, the calibration curves will be different when the material is changed.

Deviation in Die Geometry

T-Shape test is able to distinguish different friction conditions when the tooling is produced within a specified tolerance. Generally, when the tooling geometry is within the specified

allowance, the deviation of results is non-existent or not significant. In other word, the deviation of the results because of geometric tolerance should be smaller than both the accuracy of the measurement tool (load cell and geometry measurements) and the process scatter.

T-Shape B design uses 0.21 mm of half-die opening (D) (see inset from Figure 8), and 0.1 mm corner radius (r). In addition, it is necessary to define acceptable tolerance for the die design. Additional FE simulations were conducted to examine the influence of tooling inaccuracy by introducing typical tolerances of 0.01 mm and 0.05 mm (D value can be 10 and 50 μm higher or lower, see Table 3). Moreover, larger values of r were also used to illustrate the behavior when the corners of the tooling are over-polished.

Table 3: Nomenclature for different simulation settings (Tooling inaccuracy)

		D (mm)				
		-0.05 (0.15)	-0.01 (0.20)	0.21	+0.01 (0.22)	+0.05 (0.26)
r (mm)	0.1	D--	D-	N	D+	D++
	0.2	-	-	r+	-	-

Generally, larger tolerance is desirable to reduce the difficulty of tooling fabrication and reduce fabrication cost. However, too much inaccuracy would result in ineffectiveness of the friction test.

Tolerances of 0.05 mm (see Figure 14) were considered unsuitable as they strongly affect the test behavior. Although the load in D-- simulation does not deviate (from the load in D) as significantly as D++ simulation, both D++ and D-- produce significantly different geometry evolution based on simulation results. In addition, the friction curves show crossover and overlaps especially between curves of friction factor 0.1 and 0.2. Crossover and overlaps are

undesirable as they cause ambiguity –the same experimental result have more than one meaning (e.g. point marked with star in Figure 14).

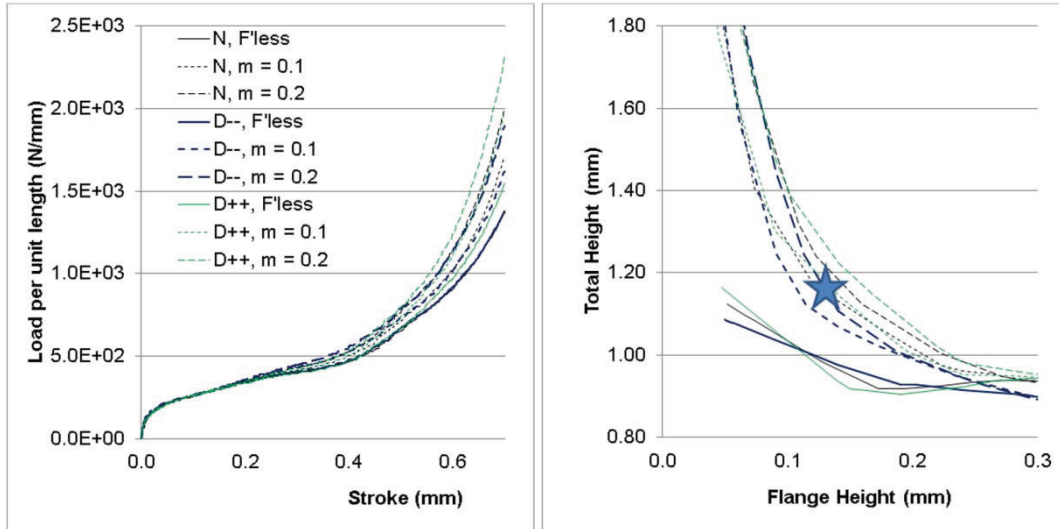


Figure 14: Effect of D to T-Shape test (larger tolerances)

Since the deviation of the results is significant, the fabrication of the test setup should use tighter tolerance. Thus, more simulations were performed using ± 0.01 mm (10 μ m) tolerances.

Figure 15 illustrates the behavior of the test using 0.01 mm tolerances.

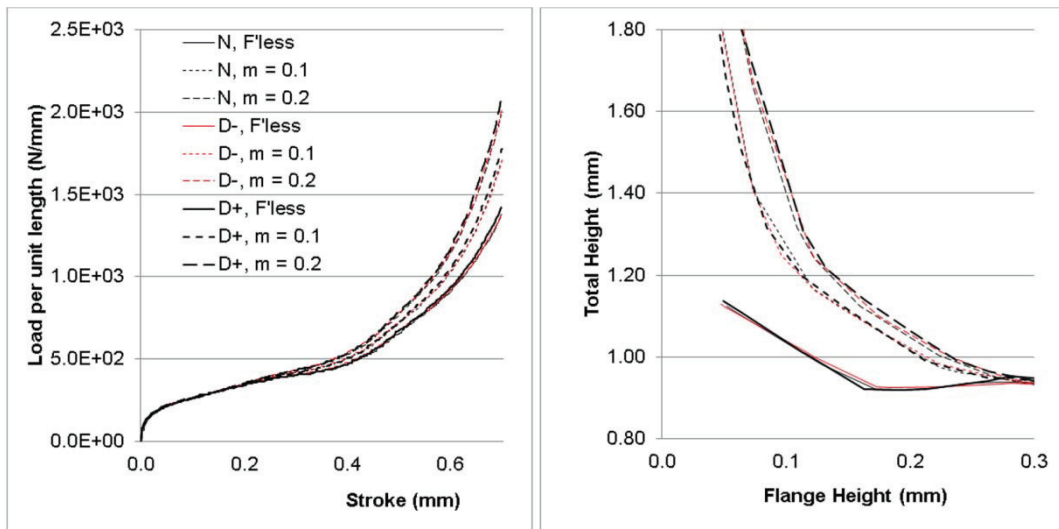


Figure 15: Effect of D to T-Shape test (smaller tolerances)

Using 0.01 mm tolerances, the loads in D^+ and D^- simulations do not deviate significantly from the load in D simulation. In addition, the influence of tolerances to the geometry evolution is only present during Stage 1 of the test; the curves converge within the measurement range (small flange height) and there is no crossover between the curves. Hence 0.01 mm tolerance is considered suitable for fabrication.

The reproduction of corner radiuses also requires extra attention. Over-polishing would result in a larger corner radius than expected and this effect is more significant as the workpiece size becomes smaller.

The simulation results show that the corner radius influences the test behavior significantly (see Figure 16). Thus, it is important to impose tight tolerance of the corner radius (possibly to 0.01 mm) to maintain good reliability of results.

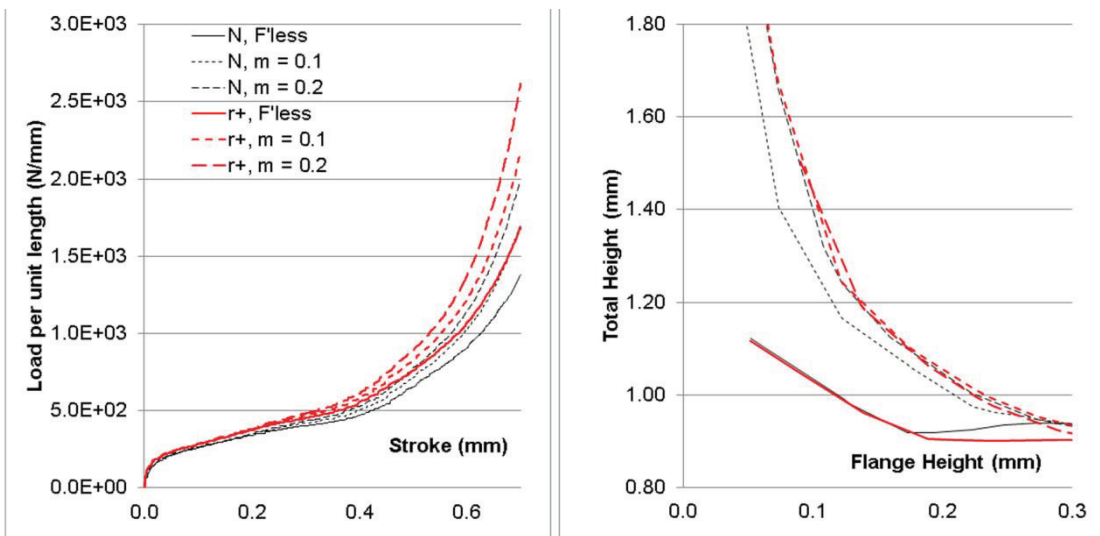


Figure 16: Effect of r to T-Shape test

Experiments

Experiments were carried out using the Schmidt Servo Press 420. The workpiece was fabricated with diameter of 1 mm and aspect ratio of 5. The T-Shape B setup in Figure 12 was prepared to be used for experiments on copper. The setup was made from heat treated Hitachi SLD Magic steel with punch and dies polished to reach surface roughness of Ra 0.1 micron.

Considering that plane strain assumption may not be representative to the workpiece with aspect ratio of 5, a more rigorous Deform 3D simulation with quarter-workpiece simulation domain (approximately 30,000 elements) was conducted to examine the experimental results. Friction sensitivity simulations were performed in order to observe the process behavior and determine the aspects from the finished geometry which are sensitive to friction. According to 3D simulation results, the two aspects which can be inspected from the finished workpiece to determine the friction behavior during T-Shape test are the width (and half-width) and total height of the workpiece at mid-length (Figure 17).

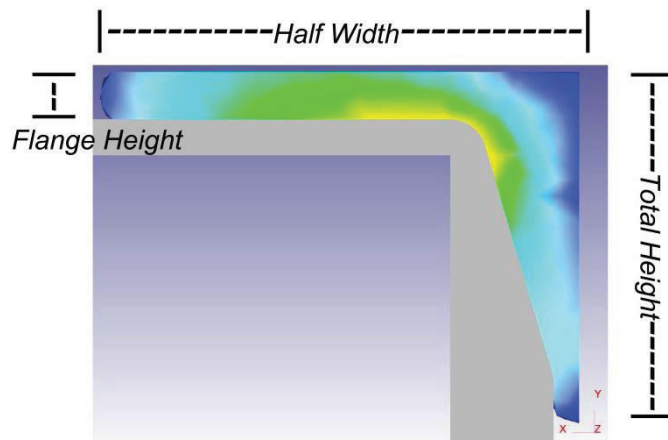


Figure 17: Half width and total height as friction sensitive aspects during test

Figure 18 presents the measurements of total height at mid-length against flange height for the 1 mm diameter workpiece and aspect ratio of 5 (without lubricant) together with the simulation results. Measurement of flange and total heights were done using an optical microscope. The experiment used 12 workpieces to provide different flange heights in order to produce a data scatter from which a conclusion can therefore be made.

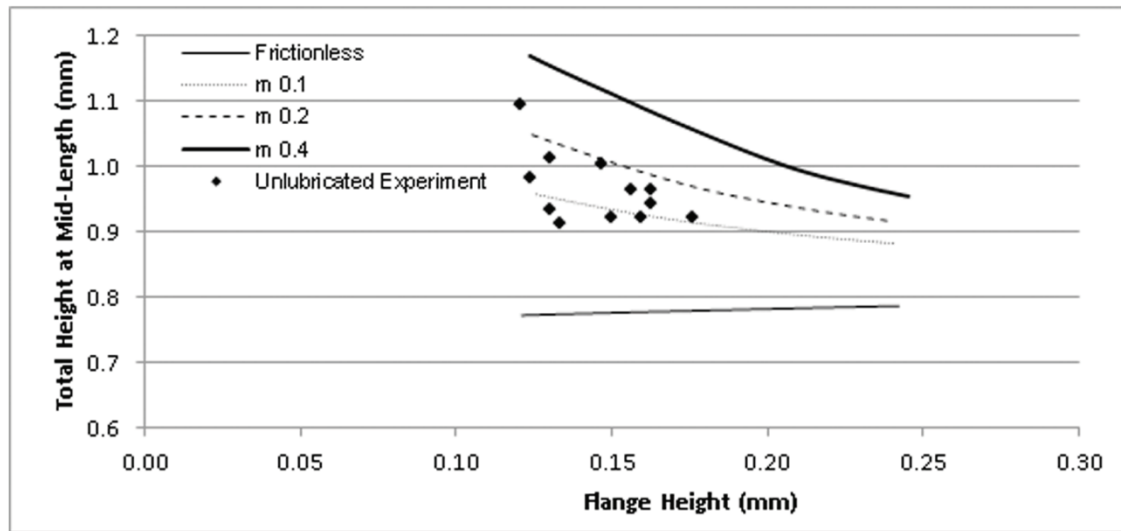


Figure 18: Comparison of total height between experimental and simulation results

Similarly, the development of the half-width between the simulation and experimental results were also compared and presented in Figure 19. It was then concluded that current experiment yielded friction factor between 0.1 and 0.2 as the data points from the experiments consistently lie between the curves produced with these friction factor values.

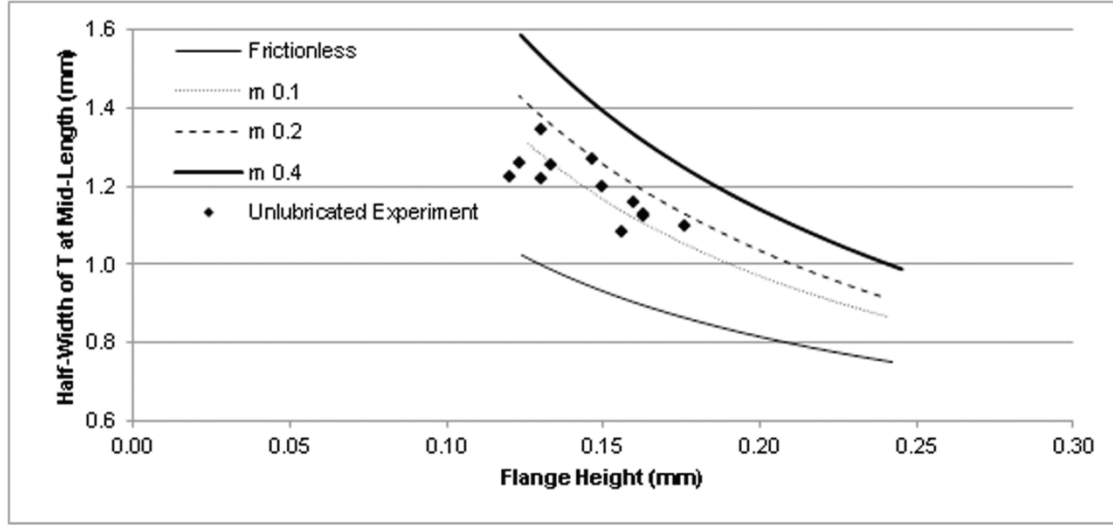


Figure 19: Comparison of half-width between experimental and simulation results

Finished workpieces were also inspected for any elastic deflection of the split die. Elastic deflection was considered negligible with small deflection of 0.01 mm observed for the 1 mm diameter workpiece.

Conclusion

T-Shape B is proposed as a friction test for microforming using considerations of the scalability of the test, the ease of specimen handling at small scale, as well as the generation of high contact pressure and severe plastic deformation. Also a new method of evaluating the results was proposed to account for possible size effects during the experiments.

Furthermore, in order to ease workpiece fabrication and handling, the aspect ratio of 5 for the T-Shape test workpiece is proposed. The modified geometry (T-Shape B) is proposed because it gives clearer distinction when the friction is within the range of frictionless to friction factor of 0.3 based on Deform 2D simulations. The acceptable tolerances were also determined from

simulations. The actual setup for 1 mm workpiece should be fabricated within 1% tolerance for the groove width and the corner radius to ensure performance of the test.

In unlubricated condition, the experiment exhibited behavior which corresponds to friction factor between 0.1 and 0.2. The benchmark simulation for this experiment was performed in 3D environment with workpiece aspect ratio of 5.

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